

NASA microgravity research highlights

# Molecules, Motors, and Monorails: Learning From Nanoscience

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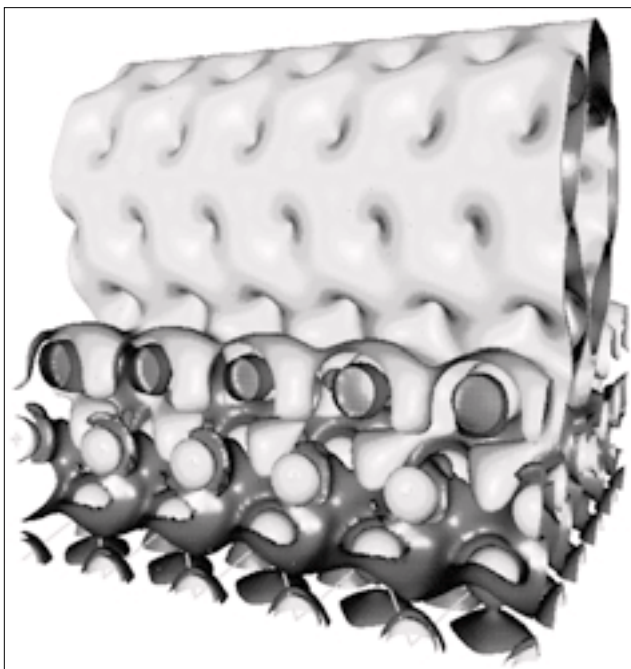
Nature has an amazing ability to heal itself. Think of what happens when you get a paper cut. Your body turns into an emergency room, sending white blood cells to ward off infection, red blood cells and proteins to form a seal over the wound, and nutrients to the dermal (skin) cells so they can produce cells to replace the ones damaged by the cut. Atoms and molecules respond on cue and know exactly where to go and what to do. Researchers funded by NASA's Physical Sciences Division are studying how nature's machines, transport systems, and communications systems work at this nanoscale so they can mimic those systems and interact with them. As they learn from the endless lessons nature has to teach, they are developing instruments and methodologies to work with components of cells that may enable more efficient space travel and change the world's approach to health care, manufacturing, electronics, and numerous other enterprises.

Research at the nanoscale involves working with molecules and subcellular parts that are measured in billionths of meters, or nanometers. Carlo Montemagno, a principal investigator in the microgravity biotechnology program and a professor at Cornell University, explains the importance of conducting research at this level: "Life is really a nanoscale organization of events. These events are not simple chemical reactions that occur because of the probability of two molecules bumping into one another - these are highly orchestrated events involving many molecules with mechanochemical functionality. The molecules are all nanomachines that do different things. They form different materials depending on how they assemble themselves, they move information from one location within a cell to another location [or cell], and they add information to the information that's going along."

## Modeling Tiny Tubes

Self-assembly, the first function named by Montemagno, intrigues Jerzy Bernholc, a principal investigator in the microgravity materials science program and a physics professor at North Carolina State University. Bernholc works with very large-scale com-

putations to model carbon molecules as they assemble themselves to form nanotubes. The strongest confirmed material known, nanotubes are much stronger than graphite, a more common material made of carbon, and weigh six times less than steel. Bernholc



The strength, light weight, and conductive qualities of nanotubes, shown in light gray in this computed electron distribution, make them excellent components of nanoscale devices. One way to conduct electricity to such devices is through contact with aluminum, shown in dark gray.

describes the material: "Nanotubes can be thought of as very strong rolled-up sheets of graphite. They're seamless tubes [that look like they are] made of chicken wire: six-sided rings with an atom at every vertex."

Nanotubes begin as fullerenes, soccer ball-shaped molecules of carbon-60 that were discovered in 1985. Researchers vaporize the molecules in a stainless steel chamber and then apply one of two methods to trigger the self-assembly of the carbon molecules into nanotubes. They either allow the carbon to condense by itself, which leads to multi-walled nanotubes, or introduce the metals nickel and cobalt as catalysts into the vapor, resulting in bundles of single-walled tubes that are a few microns to a fraction of a millimeter long and only 1 to 1.5 nanometers wide.

Bernholc is studying the growth and properties of these unique materials. Depending on how the hexagons - or in some

cases, pentagons and heptagons - are arranged, nanotubes can behave either as a metal or as a semiconductor. Bernholc says that nanotubes could be used to greatly strengthen and reduce the mass of next-generation spacecraft, while also distributing electricity. "Furthermore," he says, "the so-called 'chiral' nanotubes lose their conductivity when they are bent, so they could be used as nanoscale strain sensors. Or, when you send a current through nanotube materials, they buckle in a certain way, so they could be used as valves." Nanotubes that are conductive are attracted by an electric field impressed across them, causing them to stand up on end and form electrons. This quality will make them useful in flat-panel displays, such as computer and television screens and instrument panels, or in microwave amplifiers. Nanotube-based quantum computers also are a possibility.

In addition, because nanotubes can hold more lithium than graphite can, they could be used in more advanced batteries that could hold more power as well as be charged and discharged more quickly. Bernholc illustrates, "Plugging in a laptop to charge for, say, 15 minutes as opposed to a couple of hours is a big plus. Also, NASA could benefit from such batteries for use in various robots and exploration vehicles."

## Building Shatterproof Shells

In contrast to nanotubes, which are a new material assembled from a single element, Jeffrey Brinker, of the University of New Mexico, is studying how multiple elements can assemble themselves into a composite material that is clear, tough, and impermeable. His model? The abalone, a mollusk.

An abalone combines two simple materials to build the nacre, also called mother-of-pearl, inside its shell. The mollusk uses calcium carbonate (the main ingredient in classroom chalk) to make "bricks" and a nanoscopic layer of biopolymer as a kind of mortar. The two materials are layered to form a new material that is twice as hard and 1,000 times as tough as any of the original building materials. Brinker describes, "When you blend two or more different kinds of

materials together, usually you get some kind of composite behavior that has synergistic properties unlike those of any of the original materials.”

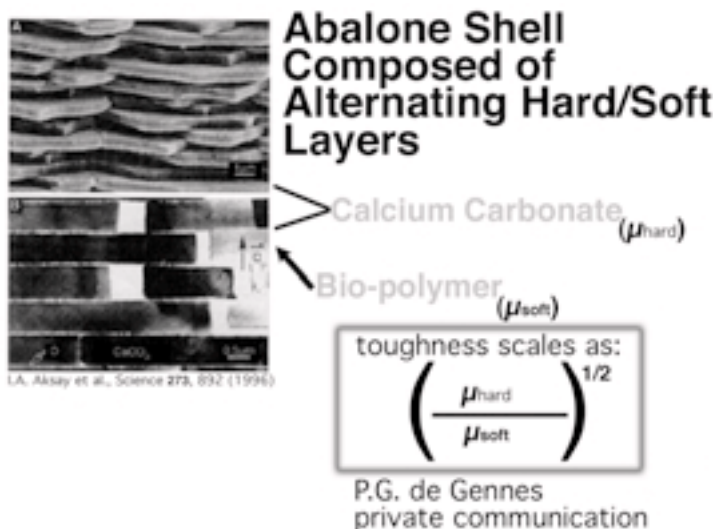
The nacre is constructed on a nanoscale through self-assembly, a sort of spontaneous organization of molecules, without any external intervention. Brinker wanted to find out if he could create a situation in which this phenomenon would occur with similar materials, and in 1998, he and his colleagues discovered they could use evaporation to trigger self-assembly of molecules into a nacre-like material. He explains, “It’s a property of certain kinds of materials that under certain conditions they will organize themselves in very precise architectures that, in many cases, would be impossible to achieve manually,

even with the best techniques available to us.” The materials they used were silicon dioxide as the inorganic bricks of the process and polymers as the organic mortar.

During the procedure, both materials are added to a surfactant solution. The surfactant causes the two precursors to assemble as molecular aggregates (micelles) with organic constituents in the interior of each particle. Brinker explains, “Surfactants are two-sided molecules: one side is hydrophilic, meaning it likes water, and the other side hates water and likes oils - we call that hydrophobic.” Evaporation accompanying simple dip-coating drives the formation of the surfactant micelles and their further organization into layered organic and inorganic assemblies composed of hundreds of alternating silica and monomer layers. Self-assembly occurs in a matter of seconds. Polymerization promoted by light or heat locks in this nano-laminated architecture, completing the composite assembly process.

Brinker explains that he could use any process that incorporates evaporation to trigger the self-assembly. “We’ve demonstrated that we can make this [protective coating] simply by dipping the substrate into a solution, and we can also do it by spraying the solution or painting it onto the substrate. We can inkjet-print this material onto a surface. We can use very small pens and write it directly onto a surface.”

The resulting layered material has numerous applications. It may prove useful as a coating for the inflatable TransHAB dwelling planned for crews



Jeffrey Brinker's research is based on the model of how an abalone builds the nacre, also called mother-of-pearl, inside its shell. The mollusk layers “bricks” of calcium carbonate (the main ingredient in classroom chalk) and “mortar” of biopolymer to form a new material (top and bottom left) that is twice as hard and 1,000 times as tough as either of the original building materials.

that land on Mars. On Earth, Brinker sees potential for use with anything that needs an optically transparent, tough coating. “Imagine coating all sorts of plastics - optical elements, computer screens, eyeglasses, all sorts of things like that. Everybody wants hard, abrasion-resistant, transparent materials.”

Brinker has further developed the material by polymerizing the surfactant, too. The result is a polydiacetylene, a polymer that has optical and electronic properties. He explains, “If we polymerize the surfactant, the nanocomposite coating becomes a very in-

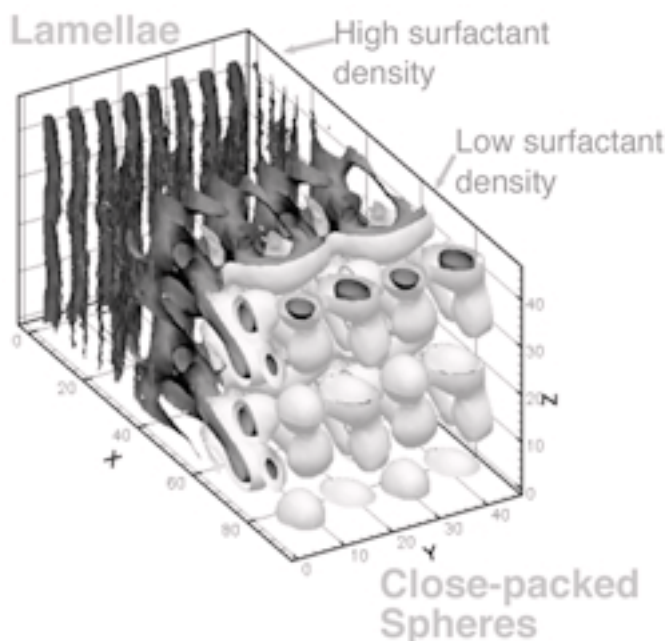
tense blue color. If you scratch that film, it will change from blue to fluorescent red. The polydiacetylene could serve as a permeation barrier, but it would also serve as a sensor for any mechanical damage [the coating] undergoes. For example, if it were abraded by the Martian atmosphere and defects formed, the defects would have this red fluorescent color that could be easily identified. That’s a way to detect where damage occurs.”

## Powering Nanomachines

In nature, when damage is detected (like a paper cut or other wound), the body goes about its mission of self-repair. But how does the body relocate the materials required to repair the damage - or for that matter, how does the body move material from one location to another for any reason? One of nature’s answers is a molecular motor, a class of machine that exists within cells. “They enable a cell to glide and move by assembling and moving pieces of materials around the sides of the cells,” explains Montemagno, who is head of the Nanoscale Biological Engineering and Transport Group at Cornell. “For example, the flagella in the sperm cell allow it to swim, and the cilia in your lungs move in a coordinated fashion to transport particles that you may breathe up and out of your mouth.”

Those organic motors require energy, which they get from adenosinetriphosphatase (ATPase), a protein used to generate power in cells. ATPase has a motor component to it - “a turbine and a generator,” specifies Montemagno - just what he needed to power the inorganic, primarily silicon-based, micromechanical devices he had already made. As he looked over data from other researchers who had made these discoveries about ATPase, he came to the conclusion that the force that a single molecule produces with ATPase is consistent with the force necessary to move the nanomachines he was fabricating. “That meant that theoretically,” recalls Montemagno, “it was possible to use this motor to move things that we could fabricate and to activate levers and things like that.”

By chemically attaching a motor protein to one of his devices and a shaft to the “rotor” of the protein, Montemagno and his research group succeeded in making their first pro-



Strong thin coatings, or lamellae, in Brinker’s research are formed when objects are dip-coated. Evaporation drives the self-assembly of molecular aggregates (micelles) of surfactant, soluble silica, and organic monomers and their further self-organization into layered organic and inorganic assemblies.

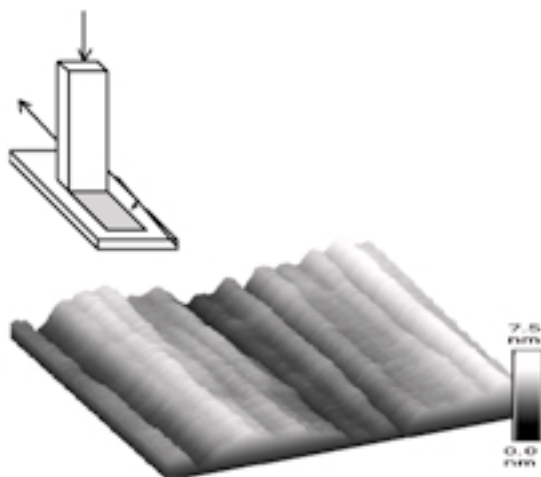
pellor last May. That enabled them to move their nanomachines with what is called rotational motion. Now, with funding from NASA, the group's goal is to be able to control the motor. Montemagno explains, "the motor has been running when it has fuel [adenosinetriphosphate, or ATP] and stopping when it runs out of fuel. We need to be able to control its fuel usage, so we've engineered a chemical switch to turn it on and turn it off, remotely." Although their latest work has not yet been published, the group first saw success with this step in their research in late December 2000.

Their other NASA-funded research involves making a mechanism for fueling the motors. Montemagno illustrates, "Now, if you want to be able to have these motors that are 10-11 nanometers in diameter, you don't want to have to use a big giant device to provide fuel for them. You want to fuel them on the same size scale. So working here with Tom Moore and other colleagues from the University of Arizona, we've developed a system of using light to produce ATP [the fuel used by ATPase] to power the motors." The auto-nomous 300-nanometers-square device can currently power nanomotors for a 12-hour light/dark cycle.

The energy produced by these tiny motors could power numerous nanodevices. One example is the "smart dust" being developed by other scientists - sensors the size of sand particles that could travel airborne and send information back to a remote computer. The "dust" may be used one day to identify areas that might be conducive to life so NASA can target areas of Mars more precisely for investigation. On Earth, the sensors could have defense applications, such as looking for chemical and biological warfare agents, or agricultural applications, such as looking for individual plants in need of pesticides or fertilizers. In the health field, the motors could act as cellular prostheses that enhance the capability of cells to produce drugs or that analyze and respond to information.

### Designing a Monorail on a Nanoscale

Even when a nanomechanical device or material for repair has the power to move from one spot to another, it still needs some kind of guidance to ensure that it reaches its destination. "We want to control the cargo transport to ensure that it is delivered to a specific point at a specific time," says Viola Vogel, director of Washington University's Center for Nanotechnology and a principal investigator for the microgravity biotechnology program. Vogel is researching what she calls a "monorail on a nanoscale" to learn



Shear-deposition of Teflon on glass (top) is used in Viola Vogel's lab to create a nanogrooved surface. The topography controls the path that microtubules take as they shuttle nano-sized cargo between user-defined destinations.

how to control translational motion of motor proteins in nonbiological environments in order to transport cargo between user-specified locations.

Nature has already evolved intricate ways of controlling the transport of molecules and large molecular complexes over long distances. In the human body, one example of nature's guidance system comes into play when the arm moves. Steve Davison, NASA's enterprise scientist for biotechnology, illustrates, "A little muscle that's in your arm contains a motor protein called myosin that moves along a filament called actin, and that's how you move your arm back and forth - this little protein climbs along the filament. So when you pull your arm in, the little protein is ratcheting up the filament like a jack, burning ATP as it goes along."

To create a nanoscale transport system for nonbiological environments, Vogel is exploring a variety of methods of microfabrication and nanofabrication tools to engineer tracks along which the motion of motor proteins can be guided. "We're also studying how to control the speed of motor proteins noninvasively and how to hook up cargo to these molecular shuttles," she adds.

Vogel's approach involved the nanoscale surface topology of glass. She explains, "On glass, the motion of a molecular shuttle powered by light-activated ATP would be random because the surface is not structured in any meaningful way." So Vogel shear-deposited a very thin Teflon film on the glass by sliding a solid block of the Teflon across it. The deposited Teflon molecules were stretched and highly oriented, with their long axes along the shear direction. The resulting surface topography featured aligned ridges and grooves running in the same direction.

Then Vogel chemically attached micro-

tubules to kineson (a motor protein) molecules. The microtubules move through the ridges and grooves like skis in a track, powered by the energy of the kineson molecules. The tiny "monorails" can follow both straight and curved "tracks."

Although her work is basically proof-of-concept at this stage - what she describes as developing the toolbox for making tracks, hooking up cargo, and controlling the speed of the "train's" movement - Vogel sees great potential for the technology: "We would like to learn how we can use this process, this transport at the nanoscale, to assemble materials in a controlled way. We also want to learn how to repair properties of materials, with a long-term goal of making self-healing materials."

### Predicting the Nano-Future

Eventually, Vogel's toolbox, as well as those of the many other principal investigators in the Physical Sciences Division who are conducting or planning research in nanotechnology, will help build materials and other resources to advance space exploration. "Nanotechnology can be used to reduce the weight and volume of spacecraft and payloads and the electricity needed to power them," says Davison. "Biological molecules or assemblies could serve as molecular-sized sensors. Harnessing macromolecules and assemblies, with their responsiveness to chemical, electrical, and light stimuli, could accelerate the development of artificial intelligence."

And that's only the beginning. As Montemagno explains, "The technologies that we're developing are emerging technologies. Expectations should be kept in the context not of 'What are you going to make for me tomorrow?' but 'What are you going to make for me five years, 10 years from now?'"

"People ask me where we are in researching nanoscience. We're at the stage right now that's the equivalent of when we figured out that we could put electricity in a wire. It's very exciting, and it's very novel, but it's really at the most fundamental level in terms of proof of concept. We demonstrate that, yeah, we can do this. Now how do we make things that are more sophisticated? What are we going to be using it all for? All that stuff has to evolve. If you think about it, when humans discovered they could send electricity through a wire, do you think they envisioned having digital watches? We can speculate and we can imagine all sorts of things that we'd like to do with it. Whether or

not those things come to fruition or some other things come to fruition is only a guess. But I am sure that this technology will develop very useful things in the relatively near future.”

### **Feynman’s Nano-Vision**

Nobel laureate and physicist Richard Feynman was one of the first people to recognize the potential of what would come to be known as nanotechnology. In his speech titled

“There’s Plenty of Room at the Bottom,” he proposed the possibility of manufacturing objects on this scale, just as nature does: “A biological system can be exceedingly small. Many of the cells are very tiny, but they are very active. They manufacture various substances, they walk around, they wiggle, and they do all kinds of marvelous things - all on a very small scale. Also, they store information. Consider the possibility that we, too, can make a thing very small which does what we want - that we can manufacture an object

that maneuvers at that level!”

Feynman also recognized that lack of instrumentation and methodology was the only thing holding back research at the nanoscale back in 1959: “In the year 2000, when they look back at this age, they will wonder why it was not until the year 1960 that anybody began seriously to move in this direction.” Now, thanks to support from NASA and many others, scientists are developing multiple approaches and instruments for nanoscience studies.

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#### **Additional information**

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